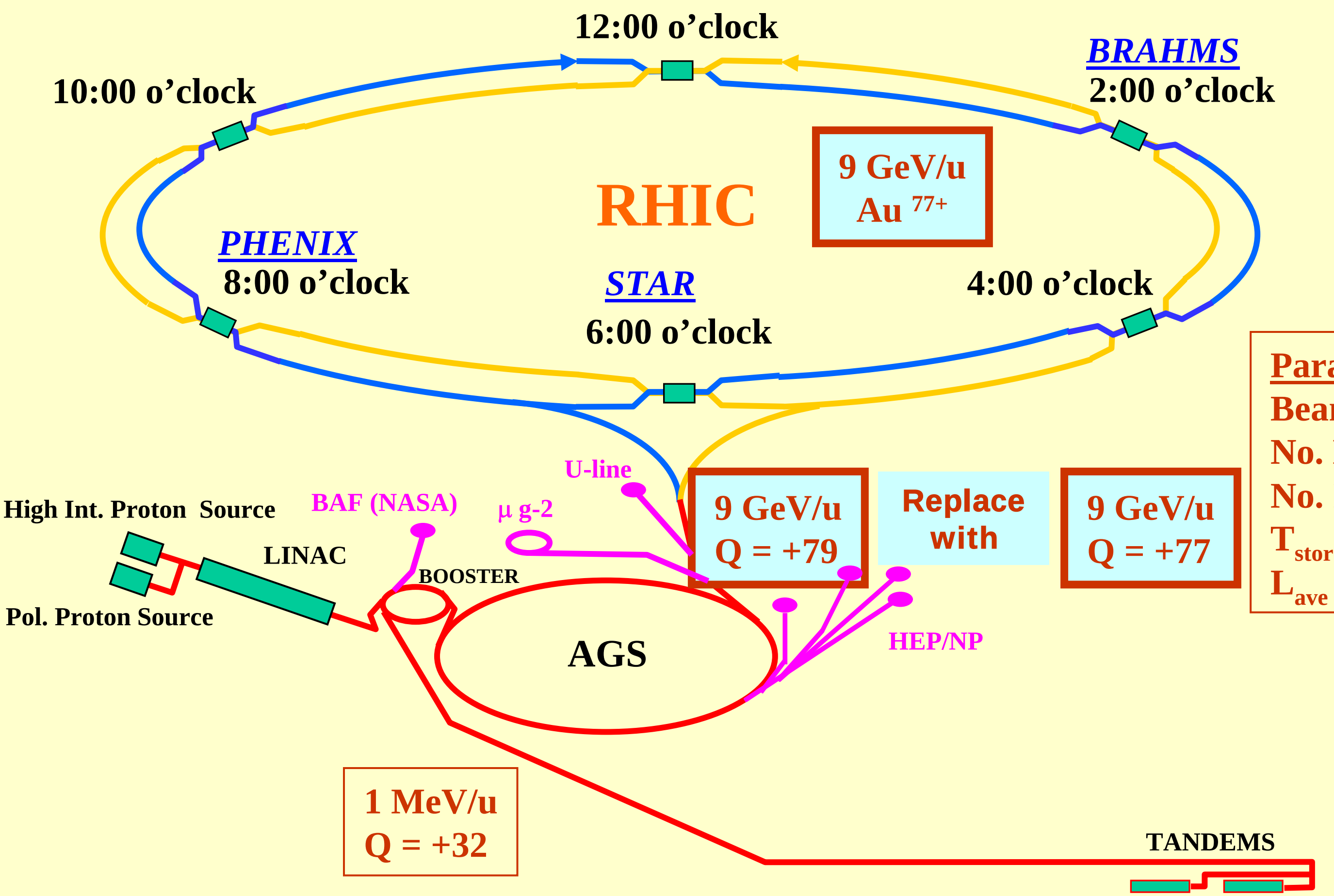
Au^{77+} in RHIC

Dejan Trbojevic

- **Introduction**
  - Remainder: injection of Au^{79+} in RHIC and Au^{77+} extraction in AGS.
  - Area of interest: IBS could be a possible cooling mechanisms, interest for collisions between not-fully stripped ions in RHIC ?, acceleration of not fully stripped heavy ions?, ...
- **Few introductory remarks:**
  - Basics of the intra-beam scattering.
  - The Barat-Fano-Lichten theory of electron promotion during ion collisions. Heavy-ion collisions, electron promotion, quasi-molecular orbital.
- **Previous proposals: Prof. Kurt Kilian-Julich, M.W. Krasny-University et Marie Curie-Paris, ...**
- **Details of the experiment proposal and participants.**
- **Possible future developments.**

Introduction: Present situation for gold run



Parameters in the next run?:
- Beam Energy = 100 GeV/u
- No. Bunches = 110?
- No. Ions /Bunch = 1-2 $\times 10^9$
- T_{store} = 10 hours
- $L_{ave} = 2 \times 10^{26}$ cm^{-2} sec^{-1}

Introduction:

- **Au^{77+} extraction in AGS, stripping @ U-line F2 flag, ATR line tuned for Au^{79+} and injection of in RHIC.**

The rest mass of fully stripped gold $m_{Au}\, c^2$ =183.4333180 GeV

$$B_{RHIC}\rho_{RHIC} = \frac{A\beta_o\gamma_o}{Zec} m_{amu}\, c^2 = \frac{197}{79}\frac{\beta_o\gamma_o}{ec} m_{amu}\, c^2$$

$$B_{AGS}\rho_{AGS} = \frac{A\beta_o\gamma_o}{Zec} m_{amu}\, c^2 = \frac{197}{77}\frac{\beta_o\gamma_o}{ec} m_{amu}\, c^2$$

$$\frac{\beta_1\gamma_1}{\beta_o\gamma_o} = \frac{79}{77}$$

$$\frac{B_{AGS\_1}\rho_{AGS\_1}}{B_{AGS\_o}\rho_{AGS\_o}} = \frac{\beta_1\gamma_1}{\beta_o\gamma_o} = \frac{79}{77}$$

– if we fix the **B**ρ in RHIC and ATR (AGS to RHIC transfer line) only the U – line part of

Phase space cooling by inelastic scattering

K. K.   ECOOL 9/84 in Karlsruhe   DPG 3/86 in Heidelberg
ECOOL 5/90 in Padua (Proceedings R. Calabrese + L. Tecchio)

- **Intra beam scattering of partially ionized ions**
  Ionization, charge transfer, elastic, inelastic

$$A^{\xi+}+A^{\xi+} \longrightarrow \left\{ \begin{array}{lll} A^{\xi+}+A^{(\xi+1)+}+e^{-} & \text{only when } \varepsilon_{coll} \gg \varepsilon_I & \multirow{2}{*}{\}\ \text{losses}} \\ A^{(\xi+1)+}+^{(\xi-1)+} & \text{threshold} < \varepsilon_I & \\ \hdashline A^{\xi+}+A^{\xi+} & \text{mixes } \Delta p_{x,y,l} & \multirow{2}{*}{\}\ \text{no losses}} \\ A^{\xi+}+A^{*\xi+} & \sigma_{inel} \sim 10^{-16}\text{cm}^2\ ? & \end{array} \right.$$

Idea: $\Rightarrow$ **inelastic & photon emission gives cooling**

- **Intra beam scattering can excite electron shells without charge changes (without beam loss)**
- **Subsequent photon emission reduces finally the relative energy ($\rightarrow$ beam temperature)**
- **Relative movement of ions in beam is damped**

$\Rightarrow$ **Avoid processes which change charges !**
$\varepsilon_{collision} < \varepsilon_I$

$\Rightarrow$ **ensure high enough collision energy** ε_{coll}
$\varepsilon_{excit} < \varepsilon_{collision}$

My special interest is here:

$$Au^{77+} + Au^{77+} \longrightarrow Au^{77+} + Au^{77+*}$$

Symmetric intra beam collisions

c. m. momentum p^*

$$p^* \Rightarrow \begin{cases} \Delta p_L \; 1/\gamma \\ \\ \Delta p_T = p_0\, \theta_{x,y} = p_0\, (\varepsilon_{x,y} / \pi \beta_{x,y})^{1/2} \end{cases}$$

c. m. collision energy $\mathcal{E}$

$\sigma_{ion-ion} = \sigma(\mathcal{E})$

$$\mathcal{E} = (p^*)^2 / M = 1/M \left[(\Delta p_L / \gamma)^2 + (p_0^2 / \pi)\, (\varepsilon_x / \beta^*_x + \varepsilon_y / \beta^*_y) \right]$$

M.W. Krasny

LPNHE, University Pierre et Marie Curie, Paris

- **COMPETITION TO eRHIC? :** **Initial idea:** **provide parasitic electron beam at hadronic colliders.**

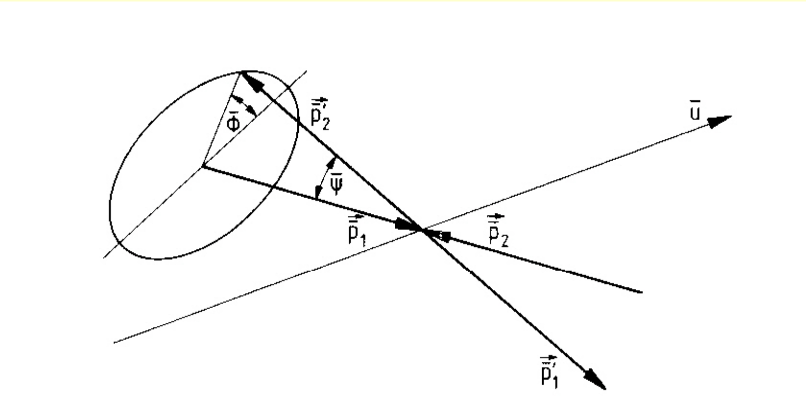
- **Leave one (or two) K-shell electrons and try to store partially stripped ions in the storage rings – get a parasitic ep (eA) collider**

  (e.g. $s^{1/2}_{LHC}$(ep) = 200 GeV)

- ***Embark on dedicated studies - preliminary results – they need to be confirmed by accelerator physicists! and tests!!***

Basics of the intra-beam scattering

Intrabeam scattering or multiple scattering is a Coulomb scattering within a bunch. Due to dispersion a change of energy always causes a change in the betatron amplitude – coupling between the transverse and longitudinal motion.



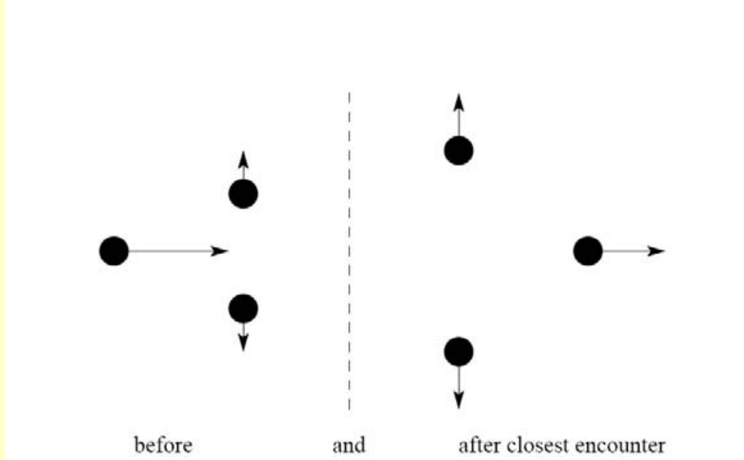


FIGURE 1. Sketch of the mechanism of dynamical friction for repelling forces between particles.

The longitudinal heating [A. V. Fedotov]:

$$\tau_{\parallel}^{-1} = \frac{1}{\sigma_p^2}\frac{d\sigma_p^2}{dt} = \frac{r_i^2 c N_i \Lambda}{8\beta^3\gamma^3\epsilon_x^{3/2}\langle\beta_{\perp}^{1/2}\rangle\sqrt{\pi/2}\,\sigma_s\sigma_p^2}.$$

A change the frame of reference:

$$p^{*}_{x,y,z} \approx \begin{cases} \Delta p_z/\gamma & \text{(longitudinal)} \\ \Delta p_{x,y} = p_0\,\theta_{x,y} = p_0\sqrt{\epsilon_{x,y}/\pi\beta^{*}_{x,y}} & \text{(transversal)} \end{cases}$$

The intrabeam collision energy which is relevant in all cross section

$$E_c = \frac{(p^{*})^2}{M} \approx \frac{1}{M}\left[\frac{(\Delta p_z)^2}{\gamma^2} + \frac{p_0^{\,2}}{\pi}\left(\frac{\epsilon_x}{\beta^{*}_x} + \frac{\epsilon_y}{\beta^{*}_y}\right)\right]$$

The transverse growth rate expressed through the longitudinal growth rate by dispersion function:

$$\tau_{\perp}^{-1} = \frac{\sigma_p^2}{\epsilon_x}\left\langle\frac{D_x^2 + (D_x'\beta_x + \alpha_x D_x)^2}{\beta_x}\right\rangle\tau_{\parallel}^{-1} = \frac{\sigma_p^2}{\epsilon_x}\langle H\rangle\tau_{\parallel}^{-1}$$

Velocity number from Alexei:

$\nu_{\text{ion velocity } x,y} = 3\times10^5$ m/s,

$\beta = 1\times10^{-3}$ $E_{kin} = 91.843$ keV !!!

Understanding the intrabeam scattering at Fermilab:

The second experiment was to demonstrate the longitudinal IBS cooling. The measurements were conducted with a bunched antiproton beam of 25×10^{10}, which was initially cooled transversely to a very small emittance (< 2 π mm-mrad). The momentum spread was increased to above 4.5 MeV/c by increasing the amplitude of the rf voltage and thus compressing the beam.

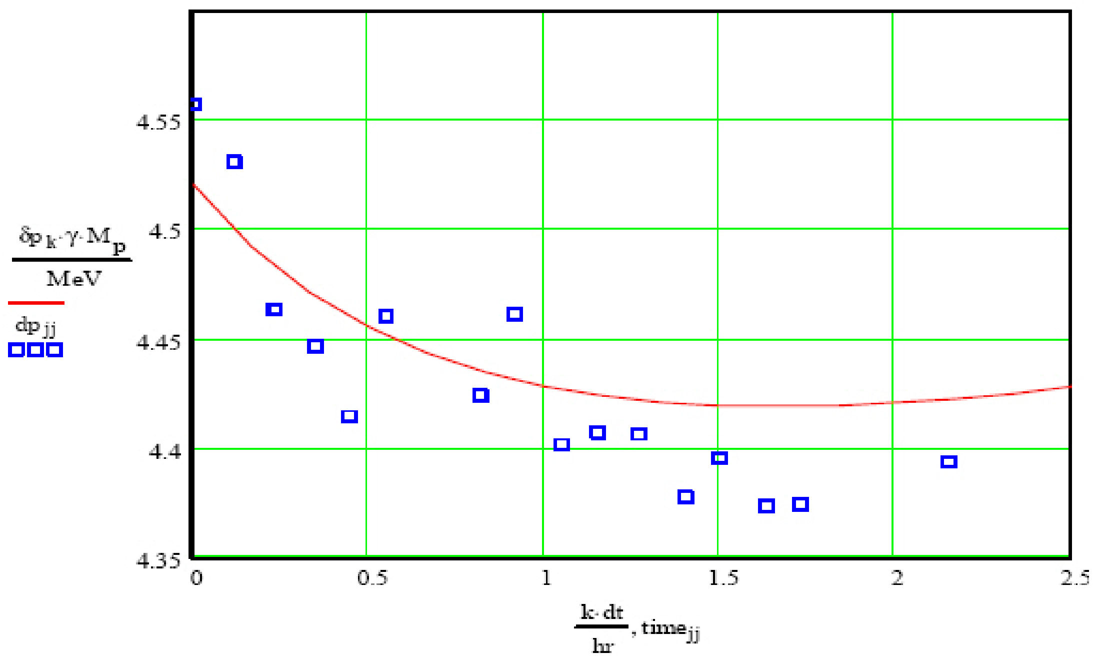


Figure 6: The longitudinal rms momentum spread (MeV/c) as a function of time (hours). The IBS model (solid line) has only one adjustable parameter – the vacuum-related transverse emittance growth rate.

Intrabeam scattering bellow transition
– equilibrium condition is possible – Fermilab results from the antiprotons

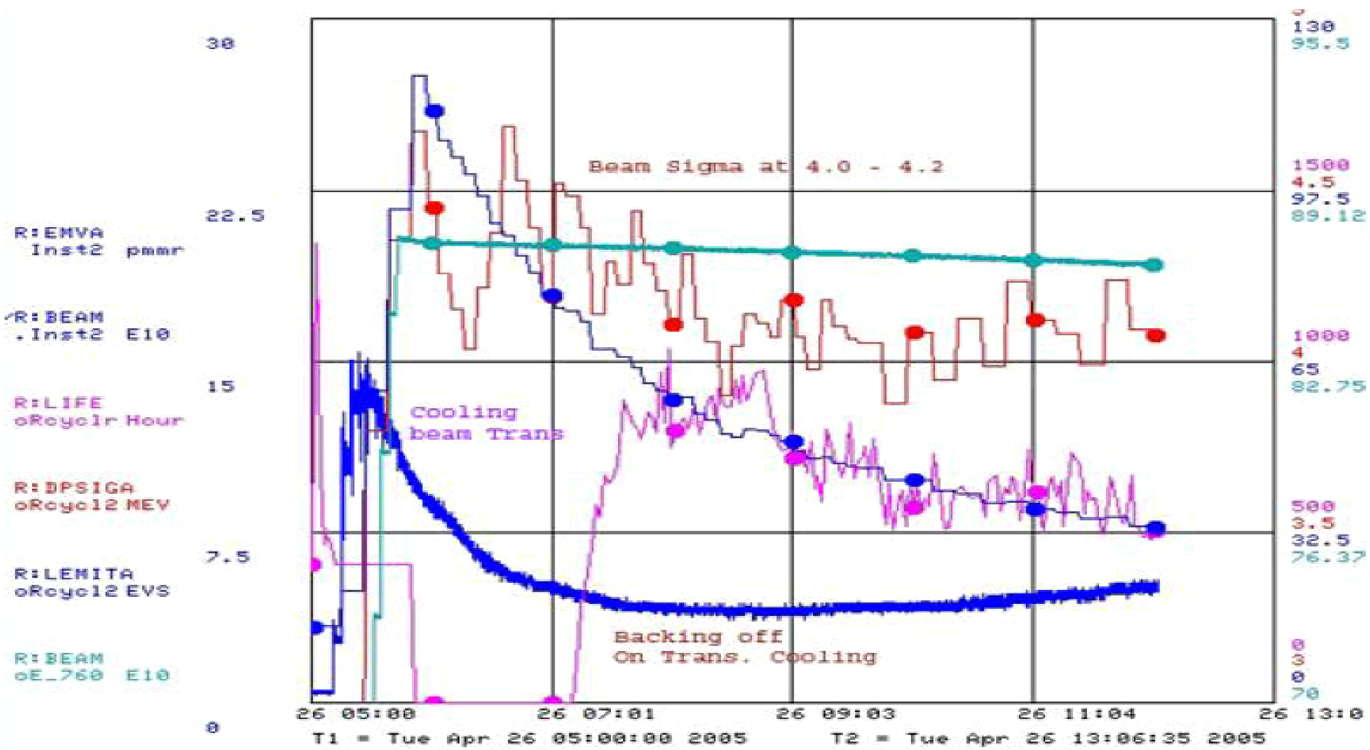


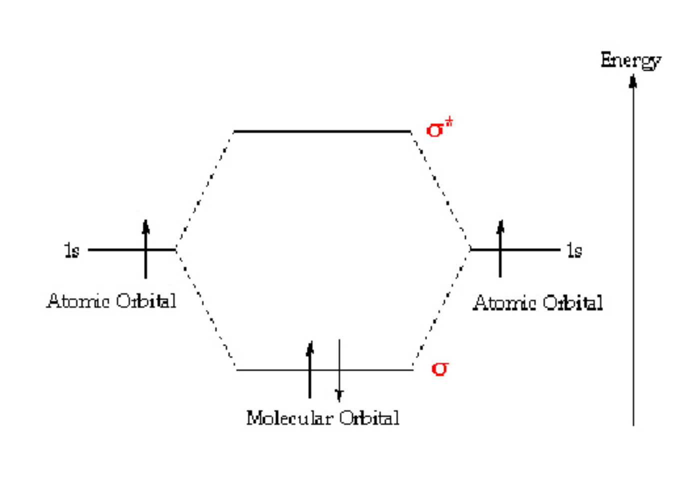
Figure 7: Demonstration of IBS-assisted longitudinal cooling: the rms momentum spread was kept at about 4 MeV/c as the beam cooled longitudinally, so as to take advantage of small IBS rate.

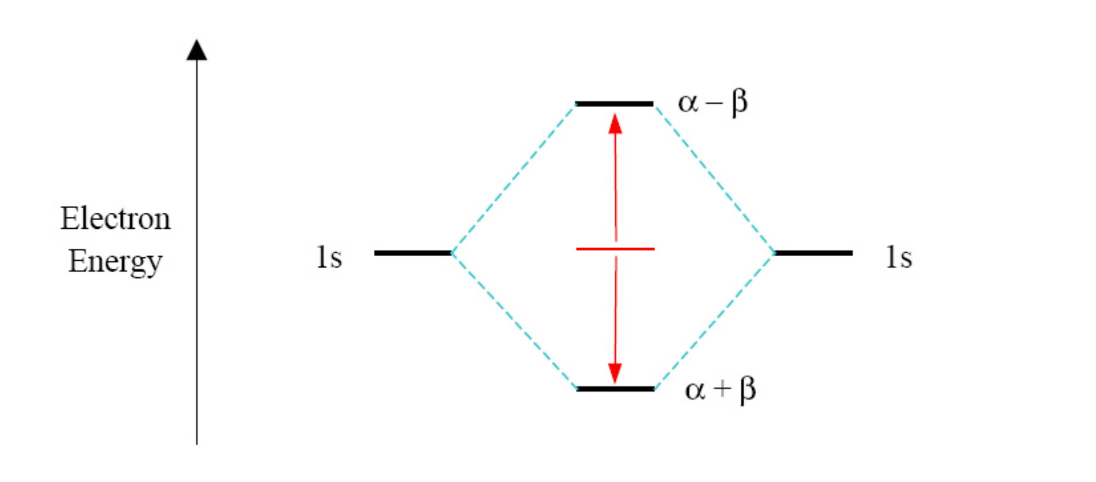
The Barat-Fano-Lichten theory

Introduction to the MOLECULAR-ORBITAL THEORY:

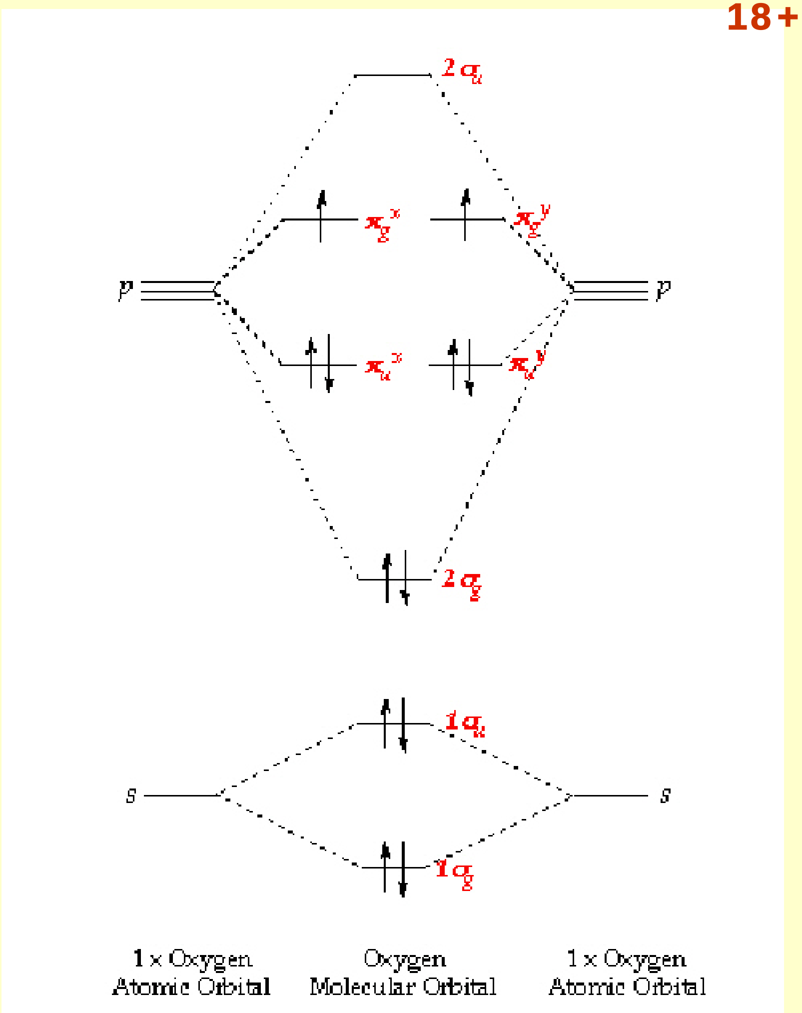
In atoms, electrons occupy **atomic orbitals**, but in molecules they occupy similar **molecular orbitals** which surround the molecule. The simplest molecule is hydrogen, which can be considered to be made up of two separate protons and electrons. There are two molecular orbitals for hydrogen, the lower energy orbital has its greater electron density between the two nuclei. This is the **bonding** molecular orbital - and is of lower energy than the two ***1s*** atomic orbitals of hydrogen atoms making this orbital more stable than two separated atomic hydrogen orbitals. The upper molecular orbital has a node in the electronic wave function and the electron density is low between the two positively charged nuclei. The energy of the upper orbital is greater than that of the ***1s*** atomic orbital, and such an orbital is called an **antibonding** molecular orbital.

Normally, the two electrons in hydrogen occupy the bonding molecular orbital, with **anti-parallel spins**. If molecular hydrogen is irradiated by ultra-violet (UV) light, the molecule may absorb the energy, and promote one electron into its antibonding orbital (s^*), and the atoms will separate. The energy levels in a hydrogen molecule can be represented in a diagram - showing how the two ***1s*** atomic orbitals combine to form two molecular orbitals, one bonding (s) and one antibonding (s^*). This is shown below - by clicking upon either the s or s^* molecular orbital in the diagram - it will show graphically in a window to the right:

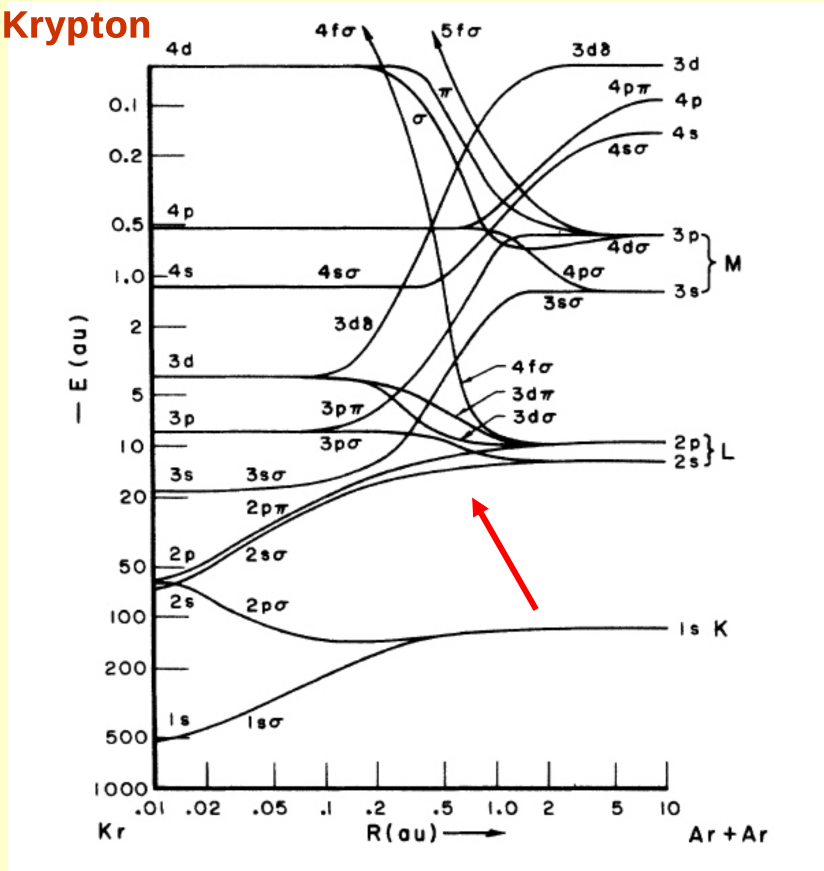




The Barat-Fano-Lichten ELECTRON-PROMOTION theory



18+18=36 Krypton



The extent of the ionization observed and, more specifically, the rapid decrease of the low-Q^* peak as r_0 enters the critical range, show that the level crossing leads with high probability to the "promotion" of electrons to outer shells, as the nuclei approach. It will be shown in a detailed paper that numerous

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150–350 keV ARGON AND NEON INDUCED X-RAY EMISSION FROM A Mo TARGET *

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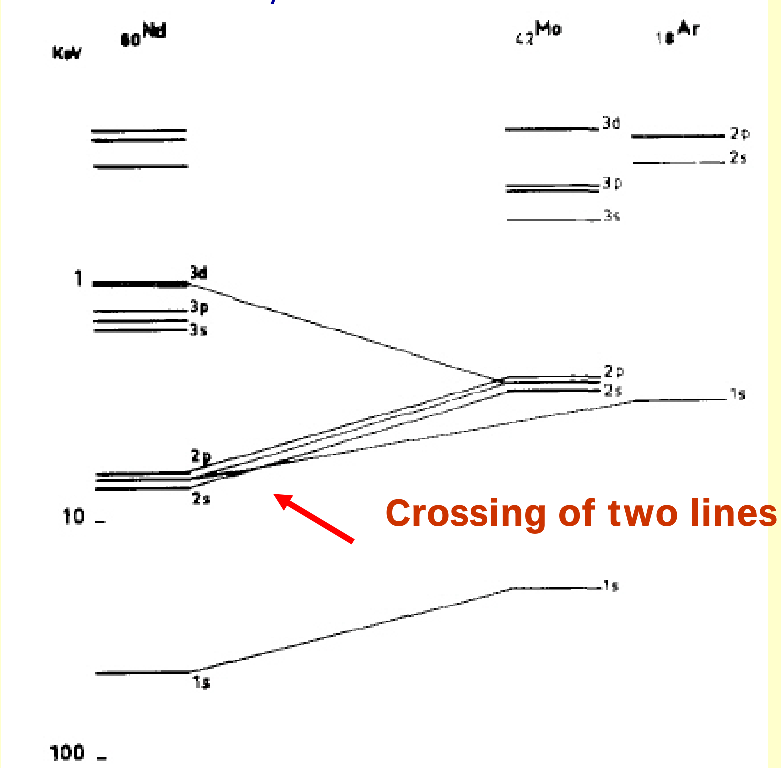
42+18=60 Neodymium



D. Trbojevic et al. / X-ray emission from a Mo target 393

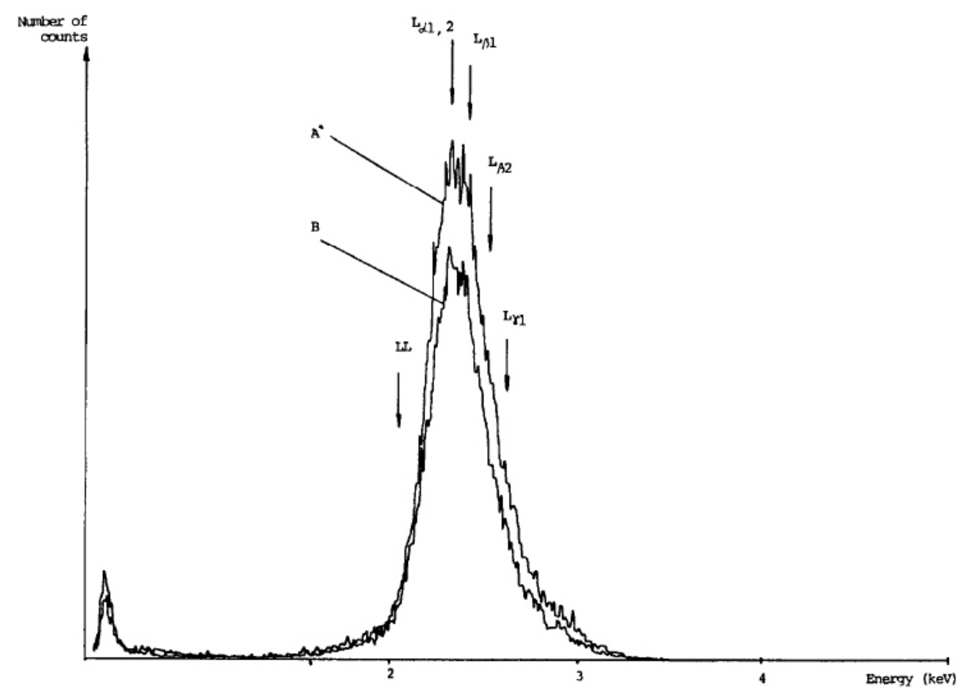


Fig. 1. The molybdenum L X-ray lines induced by Ar^+ ion bombardment with energies of 250 (curve A) and 200 keV (curve B) normalized to the ion fluences.

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K-X-RAY SPECTRUM OF THE Pb + Pb QUASIMOLECULES*

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Received 9 November 1977

We present ab initio calculations of the quasimolecular K-X-ray spectrum from the Pb + Pb system, where both the K-hole amplitude and the radiation amplitude is calculated in first order perturbation theory A comparison with the background radiation like NNB, SEB and γ-decay of excited nuclei shows that the molecular X-rays should be measurable up to X-ray energies corresponding to the characteristic K-line of the united superheavy atom

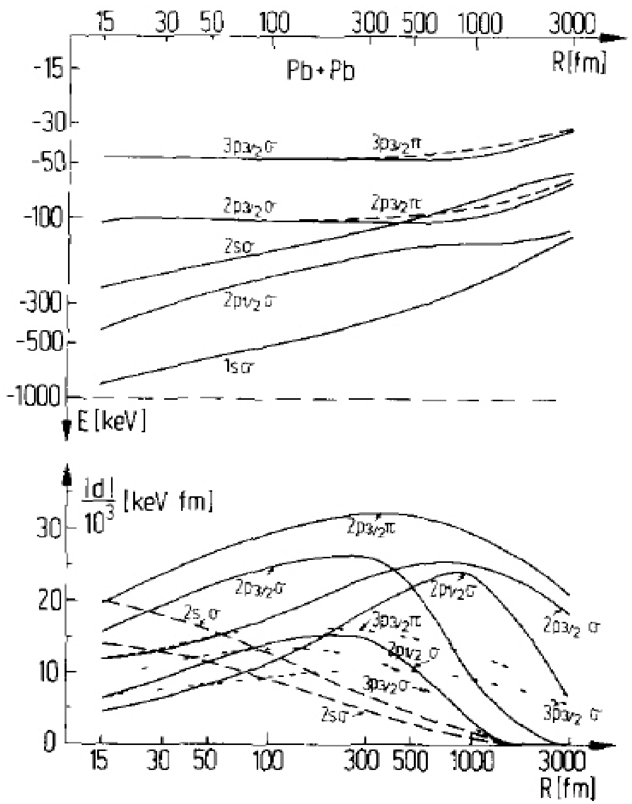
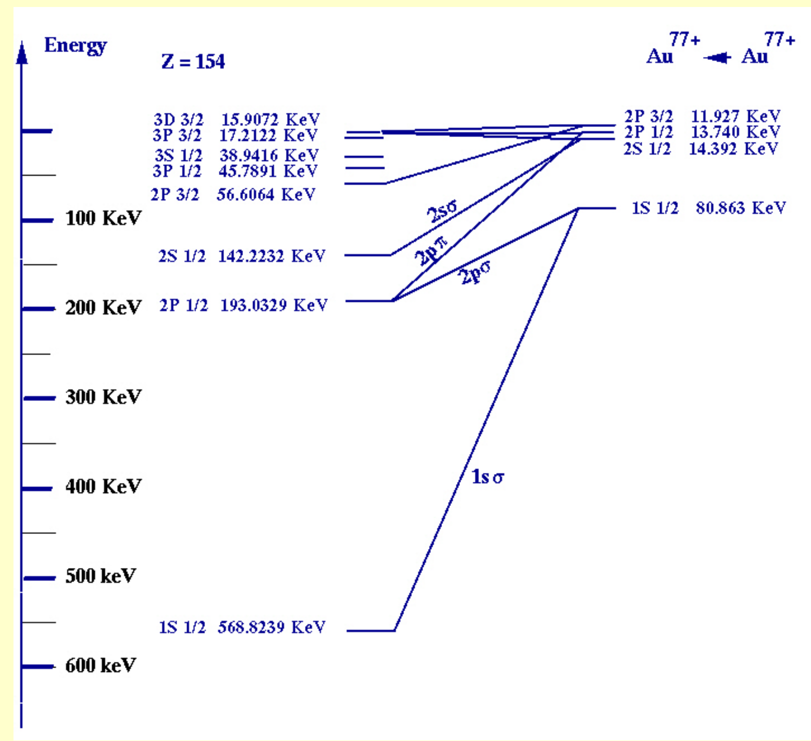


Fig 1 (a) The correlation diagram for Pb–Pb (b) The dipole matrix elements in the long wavelength approximation

My preliminary MO diagram for the Au^{77+} on Au^{77+}

United atoms



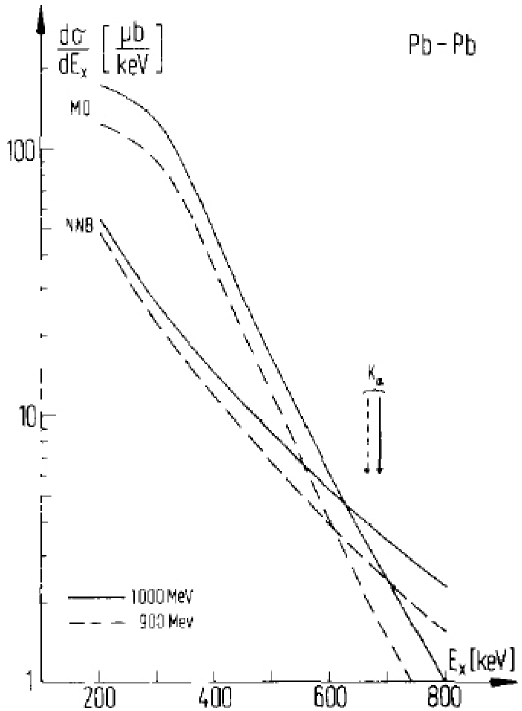


Fig 2 The M0-spectrum and the NNB background at two projectile energies The solid lines correspond to 1000 MeV and the dashed lines to 900 MeV (lab energy) The arrows indicate the K transition energy at closest approach

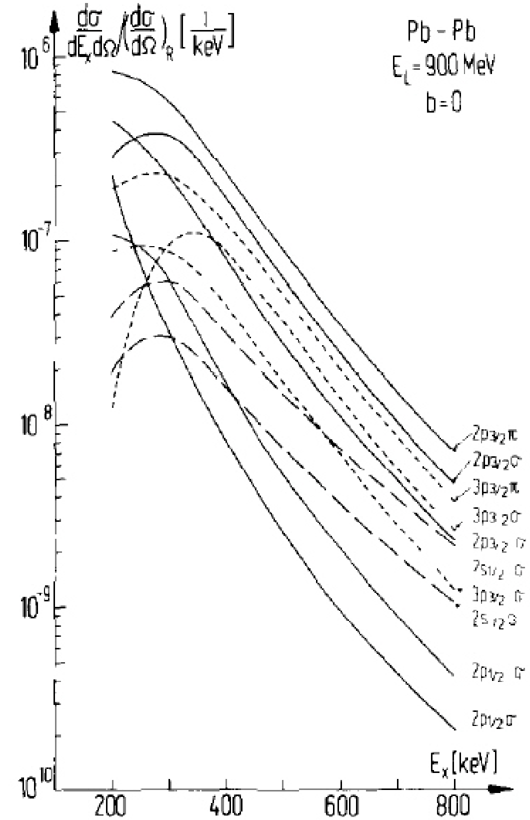


Fig 3 The contributions of the various transitions in dependence of the photon energy at zero impact parameter and 900 MeV bombarding energy

Collisions of the Helium like Gold ions with Al target

Experimental set-up

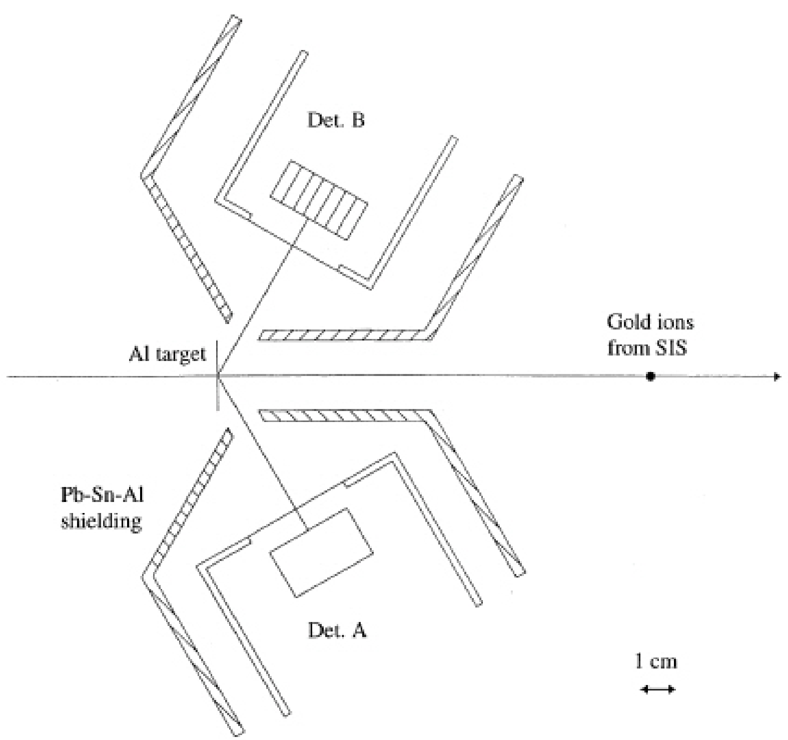


Fig. 2. Experimental setup at the target area.

Two photon decay

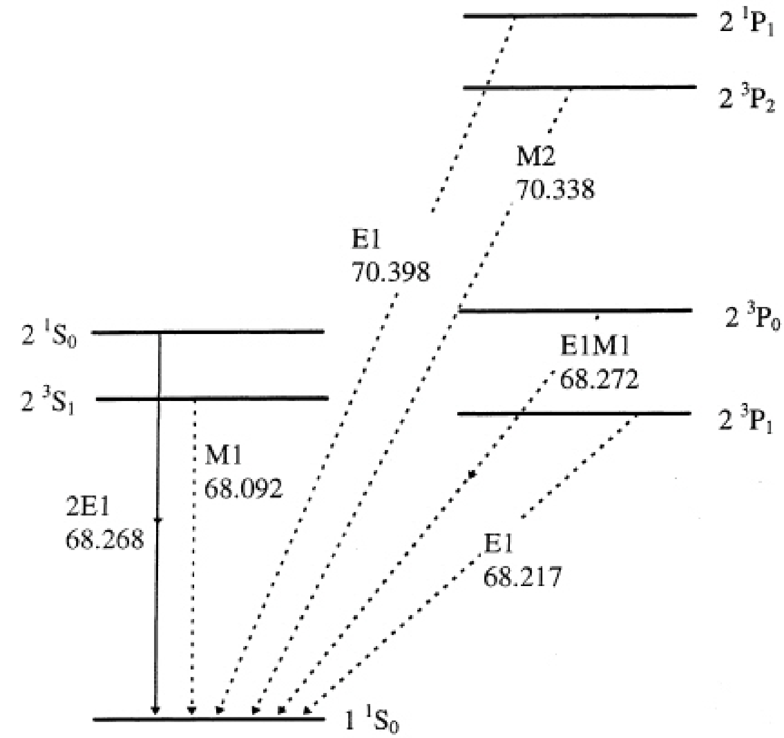


Fig. 1. Level scheme of heliumlike gold including important decay modes. All energies in keV.

Two photon-decay Au $^{77+}$ collision with Aluminum

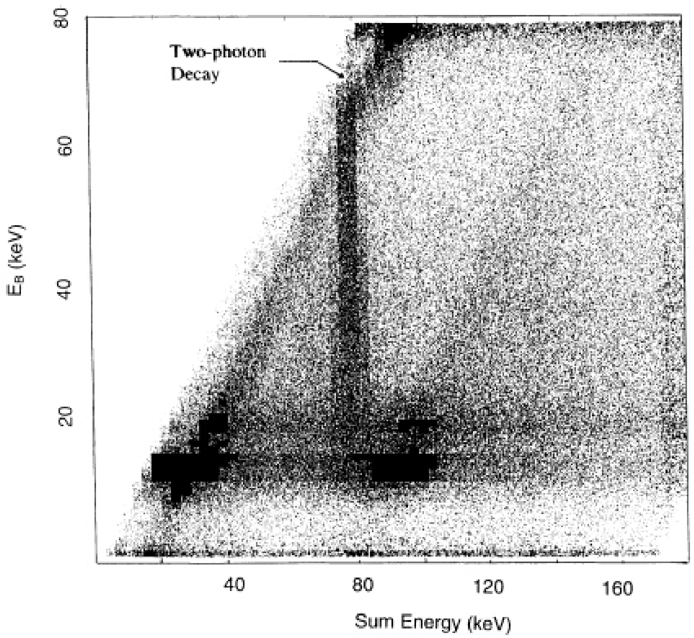


Fig. 3. Sum energy ($E_A + E_B$) vs the energy of one detector E_B for true coincidences between detector A and segment 4 of detector B.

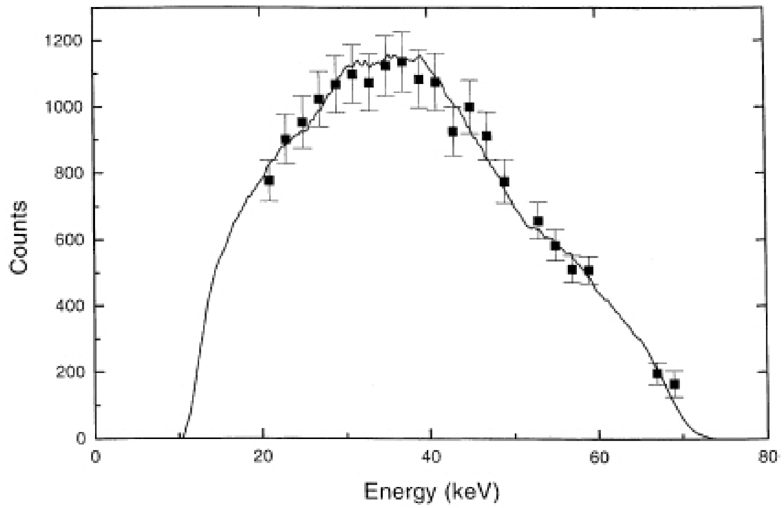


Fig. 4. Experimental data points obtained from fitting the two-photon peaks in the cuts of the sum-energy spectra (Fig. 3) as discussed in the text. The solid curve represents the Monte Carlo simulation based on the theoretical 2E1 energy distribution for heliumlike gold calculated by Derevianko and Johnson [9].

Previous proposals:

Outlook (what can be done at BNL) [M. Krasny]

- Low intensity Au(77+) beam sent to RHIC (already considered - thanks for Leif Ahren's info)?
- If successful: replace Au(79+) by Au(77+) in runs with deuterons?
- Emittance studies of the Au(77+) beam in AGS and RHIC (thanks for Dejan info)
- Direct measurement of the rates of monochromatic photons at various stages of the beam acceleration (characteristic gold excitations)
- Impact on RHIC and eRHIC (fast stripping at the top RHIC energy?, low emitance beams for eRHIC?)

Summary from Krasny's talk:

- Partially stripped high-Z ions, even if very fragile, can be accelerated and stored in LHC (and in RHIC?)
- The possible colliding partners are only fully stripped light ions.
- Partially stripped ions provide a cheep beam of monochromatic electrons
- The internal structure of partially stripped ions allows for their precise manipulation with a large list of possible side gains…
- Remaining worries: vacuum in the storage ring, Touschek effect, ???

Previous proposals:

Prof. Kilian talk at COOL2003

K. Kilian, COOL 03
23.5.03
Mt. Fuji

Phase space cooling by inelastic scattering

intra beam kinematics

orders of magnitude

- energy levels
- cross sections
- collision rates

adiabatic debunching

summary

* Atomic cross sections $\sim (10^{-8}\,cm)^2$

* Intra beam ionization NO PROBLEM

needs typical electron velocity for ions

starts when $\boxed{\mathcal{E}_{ion\cdot ion} \approx \mathcal{E}_I \underbrace{\frac{m_N}{m_e}\cdot A}_{>10^3}}$

* Charge transfer may be THE PROBLEM

$$A^{\xi+} + A^{\xi+} \longrightarrow A^{(\xi+1)+} + A^{(\xi-1)+}$$

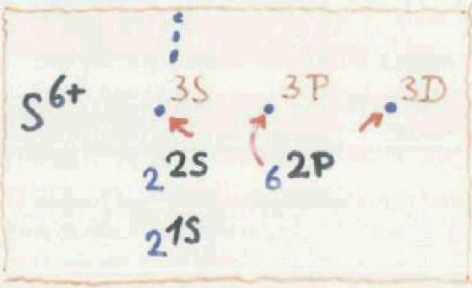
Cross sections recently from Giessen group E. Salzborn et al.

$$\boxed{\mathcal{E}_{CT} = \mathcal{E}_I \cdot k}$$

$k<1$ $\quad k \to 0$ for rising ξ $\quad k$ is shell dependent

guess: $k \sim \frac{(\xi+1)^2-\xi^2}{(\xi+1)^2}$

ξ	k
1	0,75
2	0,56
3	0,44
4	0,36
⋮	⋮
50	0,04



Hydrogen-like transitions also appear in heavier systems. Figure 2.5 is a suggested

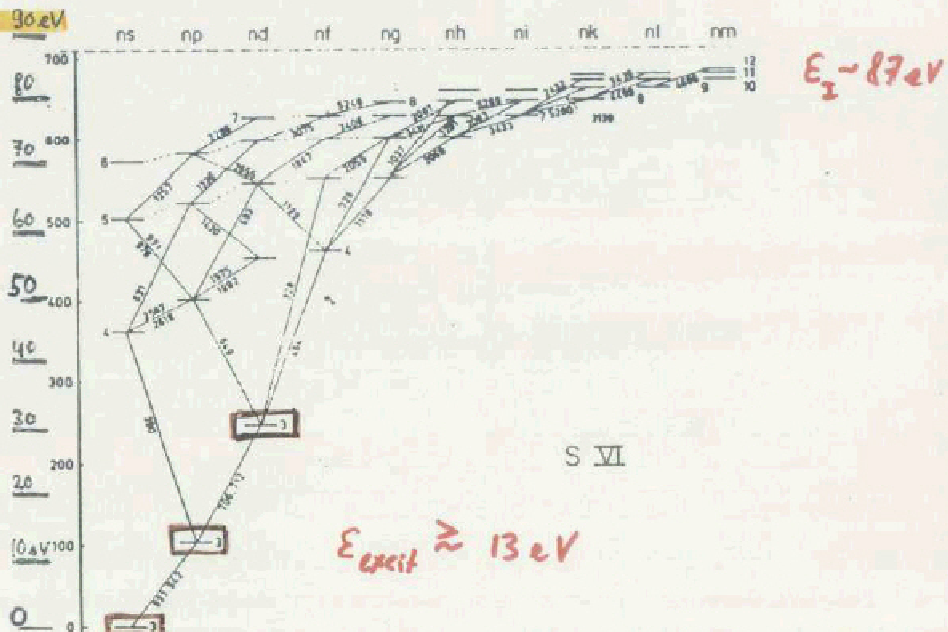
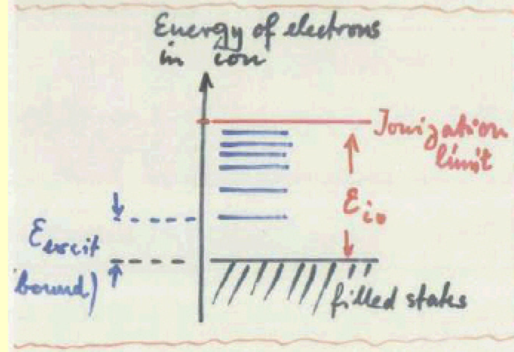
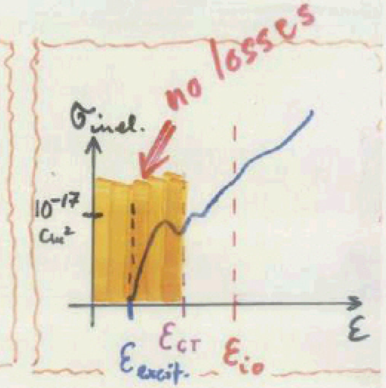
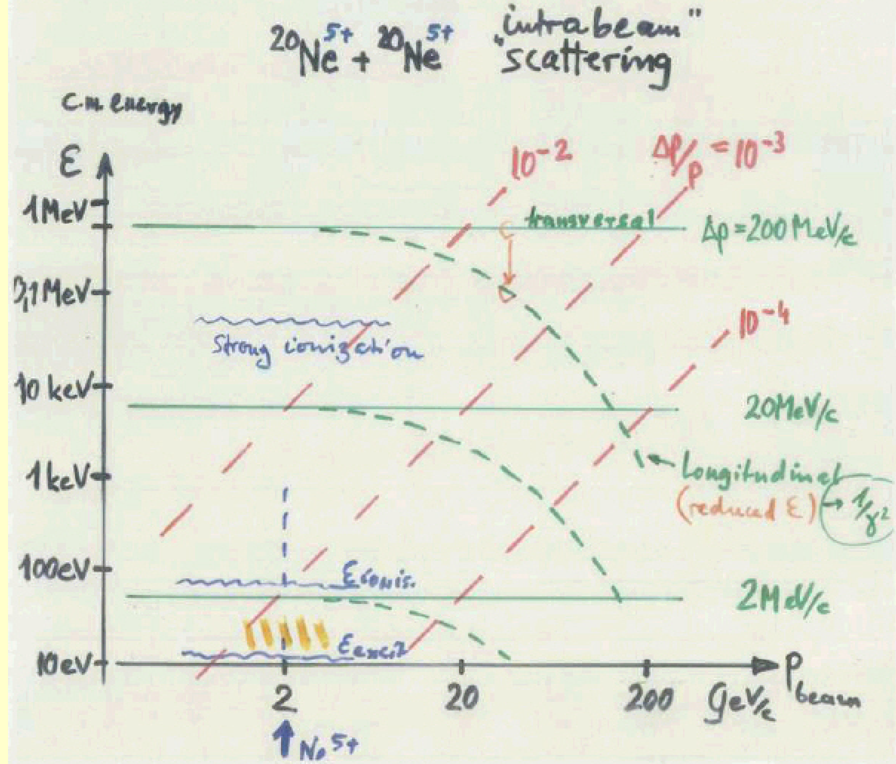


Fig.2.5 Energy level diagram for S VI. Most transitions from levels with ℓ > 3 were identified from beam-foil experiments [2.94-96]. Transition wave-lengths are in Angstrom units







Scattering rate

$$\boxed{SR = \tau^{-1} = \sigma_{ion \cdot ion} \cdot L} \qquad L = \frac{\text{target part.}}{\text{cm}^2} \cdot \frac{\text{beam part}}{\text{s}}$$

Target

$$\frac{N/2}{\text{volume}}\,\text{bunch length} = \frac{1}{2}\rho \cdot \text{bunchlength}$$

Beam

$$\frac{N/2}{\text{bunchlength}} \cdot \Delta v = \frac{1}{2}\rho\ \text{beam crosssect.} \cdot \Delta v$$

$$\boxed{L = \frac{1}{4} N^2 \frac{\Delta v}{\text{bunch volume}}}$$

Situation at TSR ?

$N \approx 2 \cdot 10^{10}$

bunchvolume $\approx 1\,\text{m} \cdot (0{,}3\,\text{cm})^2 \approx 10^2\,\text{cm}^3$

$\Delta v = 10^{-4} c = 3 \cdot 10^6\,\text{cm/s} \leftarrow \{\Delta p/p \approx 10^{-3}$ $\qquad \beta_c \sim 0{,}1$

$\hookrightarrow$ $\left.\begin{array}{l} L = 1{,}2 \cdot 10^{25}\,\text{cm}^{-2}\text{s}^{-1} \\ \sigma_{inel} \approx 10^{-16}\,\text{cm}^2 \end{array}\right\} SR = L\sigma \geq 10^9\,\text{s}^{-1}$

collision lifetime $= \frac{N}{SR} \sim 20\,\text{s}$

cooling time larger by factor $(E_{coll}/E_{incl}) \sim 10$

$\Rightarrow$ cooling time some minutes ? $(\sigma_{cr} < \sigma_{incl.}$?

Charge transfer and ionization in collisions between multiply charged noble gas ions 4077

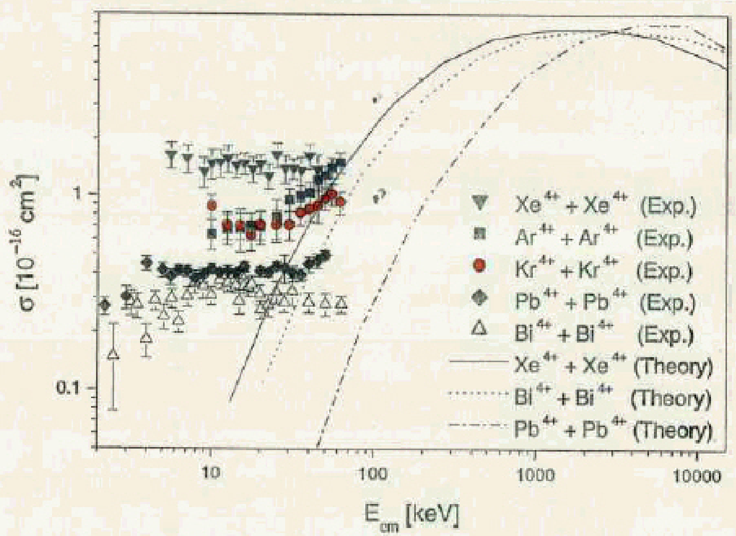


Figure 3. Comparison of the measured total charge transfer cross sections and theoretical predictions by Shevelko [11], dependent on the centre-of-mass energy. Also the experimental results for $Pb^{4+} + Pb^{4+}$ [5] and $Bi^{4+} + Bi^{4+}$ [4] are shown. For xenon the cross sections from Diemar [10] are plotted. The error bars represent the 90% confidence interval of the statistical error.

- **Details of the experiment proposal and participants**

1. **The first stage: just inject and study Au^{77+} in RHIC**
   - **Measure the emittance by IPM**
   - **Change the RF conditions**
   - **Different intensities**

2. Participants or people who have shown interest:
Leif Ahrens, Waldo MacKay, Woody Glenn, George Parzen, Mike Blaskiewicz, Mike Brennan, Christoph Montag, Mei Bai, Peter Thieberger, ...

- **Future developments:**

If there is any emittance reduction without the beam loss:

-Install the X-ray detectors to catch the electron de-excitation.
-Accelerate Au^{77+}